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COMPUTATION OF THE PRELIMINARY 1995 CATCH QUOTA FOR THE NORTHWESTERN HAWAIIAN ISLANDS LOBSTER FISHERY

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INTRODUCTION

The trap fishery for spiny lobsters (*Panulirus marginatus*) and slipper lobsters (*Scyllarides squammosus*) in the Northwestern Hawaiian Islands (NWHI) is managed by NMFS under the Crustaceans Fishery Management Plan (FMP) adopted in 1983 by the Western Pacific Regional Fishery Management Council (WPRFMC). The FMP defines a minimum legal size for harvested lobsters, requires the use of escape vents on traps, forbids the retention of berried females, and requires that vessel captains submit logbooks of daily catch and fishing effort. After logbook statistics in 1990 showed that the average catch per unit of effort (CPUE) had declined sharply (Table 1), an emergency fishery closure was enforced for several months in 1991, and the FMP was amended to provide additional protection from overfishing. Amendment 7, implemented in 1992, limited entry to the fishery to 15 permitted vessels, established a January-June closure to protect gravid lobsters before their summer spawning, and defined procedures for an annual catch quota.

The catch quota depends on the estimated lobster abundance (both species combined) in July, at the beginning of the 6-month (July-December) fishing season, relative to a predetermined "optimum" population size. Associated with the optimum population size is an optimum catch level. If the population starts the season at the optimum level of abundance and a quota equal to the optimum catch is allowed, the population will rebuild to the optimum level of abundance by the beginning of the next fishing season. If the July lobster abundance exceeds the optimum population size, the Amendment 7 quota formula allows harvest of the optimum catch plus the expected "surplus" of lobsters. On the other hand, if the July lobster abundance is less than the optimum population size the allowable quota will be less than the optimum catch, and may be zero. Expressed mathematically, the quota formula is:

$$Q = C_{opt} + [N_{est} - N_{opt}] \,, \tag{1}$$

where

Q = the number of lobsters that may be caught (the quota), legal-sized spiny and slipper lobsters combined,

C_{opt} = the optimum catch,

N_{est} = the estimated abundance of lobsters at the beginning of the fishing season (July 1),

and N_{opt} = the optimum population size.

Amendment 7 stipulates that the optimum population size and optimum catch be set to jointly satisfy the Council objectives of stabilizing the July population at a level well above the FMP's overfishing threshold and achieving an average CPUE of 1.0 lobsters per trap haul during the fishing season (Haight and Polovina, 1993).

Amendment 7 calls for NMFS to issue a "preliminary quota" in February of each year and a "final quota" by August 15, using the same quota formula. The difference between the two is that the preliminary quota uses a forecast of the July abundance derived from a mathematical model of lobster population dynamics, whereas the final quota is based on a direct estimate of the July abundance derived from July's fishery statistics. Accordingly, the preliminary quota is generally much less precise than the final quota. It is intended to assist the industry and NMFS in planning for the upcoming fishing season.

During 1992, the first year of its application, the quota procedure appeared to function well. A relatively large preliminary quota was computed. The final 1992 quota was considerably smaller (Table 2), but still sufficient to sustain the fleet for the duration of the fishing season; the total catch for the year was slightly less than the final quota. The next year, a revised population model predicted that the July 1993 lobster abundance would be too low to allow a 6-month fishery and still enable the stock to rebuild to the optimum level by July 1994. Therefore, a preliminary quota of zero was set and the fishery closed. In 1994 a preliminary quota of 200,000 lobsters was calculated and the fishery re-opened. But catch rates in July were lower than expected, with the result that a final 1994 quota of only 20,900 lobsters was computed. By the time the final quota was determined in August, the catch already had surpassed this level. NMFS then invoked an emergency closure of the fishery.

The 1994 experience was difficult for both NMFS and the fishing industry and revealed serious weaknesses in the Amendment 7 quota procedure. Among the method's flaws are its sensitivity to errors in the estimate of the July 1 population size. Under current conditions, for example, a population estimation error of only ±5% will be amplified almost 35-fold in the quota estimate. Thus, there is a high likelihood of suboptimal harvest. Further, even a slight difference between the preseason model-based population forecast and the July fishery-based population estimate can produce a large difference between the preliminary and final catch quotas and serious disruption of fishing industry operations and fishery management.

Following the 1994 fishing season, the Council convened a panel of experts to review the NWHI lobster quota management procedures and to recommend steps to improve them. The review focused on catch quota methods but also examined the history of research on NWHI lobster biology, stock assessment, and population modeling. The panel recommended that alternative quota procedures be developed that would achieve more stable and dependable harvest levels while protecting the spawning stock and minimizing the risk of recruitment overfishing.

Specifically, the panel recommended that we:

(1) Standardize the CPUE lobster abundance index using general linear modeling (GLM) procedures.

(2) Evaluate the hypothesis that recruitment declined by 50% in recent years (beginning in 1990) against alternative hypotheses that catchability decreased, natural mortality

increased, or that the trend in stock size has been biased by including both spiny and slipper lobsters in the CPUE index.

(3) Develop population models for spiny lobsters, which account for a majority of the catch, to monitor changes in that species and evaluate bias that may be associated with combining data from both species in stock assessments. Analyze both commercial and research vessel data on spiny lobsters.

(4) Develop and evaluate new quota procedures that incorporate uncertainty in the stock assessment and variability in population processes, with the goal of stabilizing catch and achieving other industry objectives while assuring a low risk of overfishing.

The panel suggested that items (1)-(3) and related work on population dynamics and stock assessment be done first, followed by the development and testing of new quota-setting procedures. It was recognized that the analytical work would be time consuming and that computations would have to be carefully checked before new quota procedures were adopted. Accordingly, our work is proceeding with a view to having a new quota procedure in place for the 1996 fishing season. The Amendment 7 quota procedure will be applied during the upcoming 1995 fishing season.

In this report, we document the computation of the preliminary quota for the 1995 season. We also present results of preliminary studies related to the panel's recommendations (1) and (2).

THE MODEL OF POPULATION DYNAMICS

The quota formula components C_{opt} and N_{opt} are determined by the magnitude of recruitment, natural mortality and catchability, as well as the target CPUE value, and are derived from a model of NWHI lobster population dynamics and catch rates published by Haight and Polovina (1993). This model states that the number of exploitable lobsters at the beginning of a month is equal to the number of lobsters at the start of the previous month, minus natural mortality and catch during the previous month, plus the month's recruitment:

$$\begin{aligned} N_{i+1} &= N_i - N_i(1-S) - C_i + R/12 \\ &= N_i S - C_i + R/12 \, , \end{aligned} \tag{2}$$

where N_i is the population size at the beginning of month i, S is the monthly survival rate in the absence of fishing, C_i is the catch during month i, and R is the annual recruitment to the exploitable stock. In addition, it is assumed that the average CPUE during a month is proportional to lobster abundance at the beginning of the month:

$$CPUE_i = qN_i \, , \tag{3}$$

where q is the catchability coefficient. Thus the model of population dynamics can be expressed in terms of CPUE as:

$$\frac{CPUE_{i+1}}{q} = \frac{CPUE_i}{q}S - C_i + R/12 \ . \tag{4}$$

As described by Haight and Polovina (1993), the model parameters (S, q, and R) are estimated by fitting this equation to monthly statistics on CPUE and catch using least-squares methods. Because of spatial and temporal variation in population and fishery dynamics, catches of both lobster species are combined and data are pooled over fishing areas to calculate a composite NWHI monthly average CPUE. As new catch and CPUE data are added to the historical data base the model is updated. Estimates of C_{opt} and N_{opt} are recomputed annually as information on the basic parameters is improved.

Assuming that S, q, and R were constant over time, Haight and Polovina (1993) fit the population model to commercial CPUE data from 1983 through 1992. They found that the model fit quite well through 1989, but tended to overestimate observed CPUE after 1989 (Fig. 1). Based on oceanographic and population studies by Polovina and Mitchum (1992), Haight and Polovina (1993) attributed the poor fit of the model after 1989 to a change in recruitment. They rejected alternative hypotheses that the catchability had declined or natural mortality had increased. Subsequently, they fit the model to the same CPUE data assuming a two-phase recruitment: a high value that prevailed through October 1989, and a lower value thereafter. The more elaborate model fit the data much better (Fig. 1).

DID RECRUITMENT DECLINE AFTER 1989?

As recommended by the review panel, we evaluated alternative hypotheses that might account for the drop in commercial CPUE in recent years. To do so, we fit the dynamic population model under three sets of conditions:

Hypothesis A - change in survival

R, q, are assumed to be fixed constants. The monthly survival rate is assumed to be at one level, $S_{(1)}$, through October 1989, and a second level, $S_{(2)}$, afterward.

With R = 1,673,949, q = 7.32×10^{-7}, and $S_{(1)}$ fixed at 0.963, the analysis estimated $S_{(2)}$ = 0.875; i.e., a 3.4-fold increase in the natural mortality rate of exploitable lobsters (Fig. 2). We have no evidence to substantiate a change in natural mortality of this magnitude. This hypothesis is considered to be unreasonable.

Hypothesis B - change in catchability

In this case, S and R are assumed to be fixed constants. Catchability is assumed to be at one level, $q_{(1)}$, through October 1989, and a second level, $q_{(2)}$, afterward.

With S = 0.963, R = 1,673,949, and $q_{(1)}$ fixed at 7.32×10^{-7}, $q_{(2)}$ was estimated at 3.143×10^{-7}, a 57% reduction in catchability (Fig. 3). We have found no evidence that such a drop in q could have been caused by changes in commercial fishing practices; fishing strategies and vessel efficiencies have remained fairly constant. Moreover, CPUE statistics from research vessel surveys, which have maintained standard gear and fishing protocols over the years, are highly correlated with commercial fishery CPUEs during the same months (Fig. 4). Thus, a 57% drop in commercial vessel catchability is unlikely.

Hypothesis C - change in recruitment

In this case, described above and shown in Fig. 1, S and q are considered fixed constants. Recruitment is assumed to be at one constant level, $R_{(1)}$, from 1983 through October 1989, and at a different level, $R_{(2)}$, from November 1990 onward.

With S = 0.963, q = 7.32×10^{-7}, and $R_{(1)}$ fixed at 1,673,949, $R_{(2)}$ was estimated at 741,679. Thus, the reduced CPUE since 1990 is consistent with a 56% drop in recruitment of legal-size lobsters. Support for this hypothesis is provided by age composition changes at two major fishing areas, analyses of spawning biomass per recruit, and oceanographic studies. Most lobsters recruit at an age of 3 years. Age composition data from *Townsend Cromwell* research surveys at Maro Reef show that not only did CPUE decline in all age classes between 1988 and 1990 (no data are available for 1989), and remain at a reduced level through 1992, but the proportion of lobsters older than 3 yr increased; both of these changes in age composition are indicative of a decline in recruitment (Fig. 5a). At Necker Island, 670 km southeast of Maro Reef, a similar decline in the abundance of 3-yr-old lobsters was observed, but the overall abundance was relatively stable (Fig. 5b).

With respect to spawning biomass per recruit (SBR), analyses indicate that during 1985 and 1986 SBR was approximately 40% of its expected level in the absence of fishing, suggesting that spawning biomass was not fished down to a level that would cause poor recruitment to the fishery during 1989-90 (Haight and Polovina, 1993).

Reduced NWHI lobster recruitment after 1989 is also consistent with an apparent decline in central North Pacific biological productivity at various trophic levels, following a period of enhanced primary productivity in the early 1980s. As described by Polovina et al. (1994), the period of increased productivity, during which lobsters and other species were at higher levels of abundance, was associated with decadal climate changes over the North Pacific. The subsequent decline in primary productivity likely resulted in lower survival of lobster larvae and reduced recruitment. Similar links between climate events and recruitment have been demonstrated in western rock lobster (Pearce and Phillips, 1988). In addition to the influence of climate on ocean productivity, associated variations in ocean circulation can alter recruitment by affecting larval transport. Polovina and Mitchum (1992) found that lobster recruitment at Maro Reef was correlated with the difference between sea level measurements at French Frigate Shoals and Midway Island 4 years earlier. The sea level difference between French Frigate Shoals and Midway Island reflects the strength of the Subtropical Countercurrent, which is thought to affect transport and survival of late-stage larvae at Maro Reef. The sea level anomaly is not correlated with lobster recruitment at Necker Island, but this may be explained by differences in the ocean circulation patterns affecting larval transport to the two banks.

In summary, of the three alternatives, a drop in recruitment is the most reasonable explanation for the observed reduction in lobster CPUE between 1989 and 1990.

IMPROVING INDICES OF ABUNDANCE

Previously, monthly lobster abundance indices used in the dynamic population model had been computed as the observed arithmetic average CPUE, using catch and effort statistics summarized by month. As recommended by the review panel, we conducted a general linear model analysis of CPUE to determine the effects of various factors on monthly average CPUE and to derive indices of abundance adjusted for such effects. Preliminary linear models were explored with factors which might measure the degree of species targeting, within-month depletion, and vessel fishing power, but these analyses proved to be complicated and will require further study.

We also examined the effect of another factor, the area of fishing (bank). If average catch rates vary significantly between banks, temporal differences in the distribution of fishing effort could bias the aggregate CPUE index. An analysis of variance (ANOVA) was computed with the model:

$$y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + \epsilon_{ijkl}, \tag{5}$$

where

y_{ijkl} = natural logarithm of average CPUE for the l-th vessel-day of fishing in the k-th fishing area during the j-th month of the i-th year;

μ = overall mean of the log-transformed CPUE's;

α_i = effect of the i-th year;

β_j = effect of the j-th month;

$(\alpha\beta)_{ij}$ = interaction effect of the i-th year and j-th month;

γ_k = effect of the k-th fishing area (bank);

ε_{ijkl} = random error term.

We log-transformed the CPUE data to normalize model error and stabilize error variance, as required by the ANOVA's F-tests. Using the GLM procedure of SAS (SAS Institute, Inc., 1990), we computed F statistics to test the null hypothesis that the bank effect was zero; i.e., that the average monthly CPUE did not vary by bank. This hypothesis was rejected; the F-test showed that the "bank effect" was highly significant (Table 3). This result was not unexpected, as summary statistics have indicated considerable CPUE variation between banks (Table 4). Accordingly, we computed from the GLM a series of monthly mean log (CPUE) values which were adjusted for monthly differences in effort distribution among banks (so-called "least-squares means"). Corresponding adjusted mean CPUE statistics, in the original arithmetic units, were computed by back-transformation, incorporating proper bias corrections. The adjusted monthly CPUEs are generally close to the unadjusted data (Fig. 6).

UPDATED POPULATION MODEL

The dynamic population model described above was fit to the bank-adjusted 1983-1994 commercial CPUE data to update estimates of the parameters $R_{(1)}$, $R_{(2)}$ and q. Note that the bank-adjusted CPUEs were computed by averaging individual vessel-day CPUE statistics. In previous cases (Figs. 1, 2 and 3) the average CPUEs were based on aggregated monthly catch and effort statistics.

With the value of S fixed at 0.963, the analysis estimated $R_{(1)} = 1{,}686{,}695$, $R_{(2)} = 756{,}471$ lobsters per year, and $q = 7.17 \times 10^{-7}$ per trap haul. For purposes of computing C_{opt} and N_{opt} (see below), we set $R = R_{(2)} = 756{,}471$ lobsters.

The fitted model was used to forecast the July 1995 exploitable lobster population at $N_{est} = 1{,}328{,}202$ lobsters (Fig. 7). The predicted July 1995 CPUE is 0.952 lobsters per trap haul.

COMPONENTS OF THE CATCH QUOTA AND RELATED ANALYSIS

In past years, estimates of C_{opt} and N_{opt} were derived by iterative numerical approximation using a spreadsheet simulation model of lobster population dynamics. In this procedure the estimates of R, S and q were inserted into the spreadsheet, along with initial approximations of C_{opt} and N_{opt}. The model was run and values of C_{opt} and N_{opt} modified until the joint constraints of a stable July 1 population size and average CPUE equal to 1.0 lobsters per trap-haul were satisfied.

This year we improved the computation of C_{opt} and N_{opt} by deriving exact analytical formulas for them (Appendix); these formulas replaced the spreadsheet procedure.

Further, using the exact expressions for C_{opt} and N_{opt} we derived analytically the exact formula for the catch quota, Q^*, consistent with Amendment 7 management objectives:

$$Q^* = C_{opt} + \beta [N_{est} - N_{opt}] , \tag{6}$$

where ß is a coefficient between zero and one whose value depends on the natural mortality rate and the duration of the fishing season (Appendix). It is evident from this exact quota result that the Amendment 7 quota formula is an approximation, as it does not account for natural mortality. The closeness of the approximation depends on three factors: the natural mortality rate, as reflected in ß; the difference between N_{est} and N_{opt} as a fraction of N_{opt}; and C_{opt}/N_{opt}, the optimum harvest ratio. When N_{est} exceeds N_{opt} the approximation will exceed the exact quota result by no more than (1-ß)/ß percent. Given the current estimate of ß = 0.87, such a positive bias would be less than 15 percent. Underestimation of the exact quota by the Amendment 7 approximation when N_{est} is less than N_{opt} would be comparatively greater, particularly if the optimum harvest ratio is low. When the Amendment 7 quota procedures were adopted the exact analytical results were unknown. In retrospect, however, use of the exact quota formula instead of the Amendment 7 approximation would not have altered key NWHI lobster management decisions. Because the approximate quota formula is stipulated in Amendment 7 it was used below to compute the 1995 preliminary quota.

COMPUTATION OF THE 1995 PRELIMINARY QUOTA

The preliminary catch quota for the 1995 NWHI lobster fishing season was computed using the Amendment 7 quota formula, updated estimates of C_{opt} and N_{opt}, and an estimate of the July 1995 population size projected from the population model.

The parameter estimates were:

C_{opt} = 134,494 lobsters

N_{opt} = 1,424,183 lobsters

N_{est} = 1,328,202 lobsters

Therefore, the preliminary quota is:

$$Q = 134{,}494 + (1{,}328{,}202 - 1{,}424{,}183)$$

$$= 134{,}494 - 95{,}981$$

$$= 38{,}513 \text{ lobsters.}$$

The Amendment 7 quota determination procedures assume that the quota will be taken in equal monthly increments over the fishing season, from July through December. In practice, however, the quota could be taken at a faster rate. Amendment 7 procedures require that the fishery be closed when the quota is reached or on January 1, whichever occurs sooner.

FUTURE COURSE OF ACTION

The preliminary quota figure was submitted to the NMFS Southwest Region in January 1995, for evaluation and further action. Based on the preliminary quota level and other considerations, NMFS will determine the appropriate course of action with respect to the 1995 NWHI fishing season and publish its determination on a timely basis.

In the coming months we will continue research to improve the NWHI lobster fishery management procedures, taking into consideration recommendations of the review panel. The research will involve four interrelated projects:

(1) Data management

To ensure a comprehensive, identifiable database for population modeling and fishery management research, all lobster data collected from the NWHI commercial fishery and research cruises will be assembled and systematically documented.

(2) Abundance indexing

To derive the best index of lobster abundance, CPUE statistics will be analyzed using a variety of statistical procedures, including Generalized Linear Models (GLM), General Additive Models (GAM) and time series analysis. Indices will be developed that account for factors which may affect lobster catchability. The factors to be considered include changes in fleet composition and vessel fishing power, changes in species targeting, variation in within-month depletion rates, and changes in area of fishing. To the extent possible, separate abundance indices will be developed for each species and bank.

(3) Population dynamics and biological reference points

The current model of NWHI lobster population dynamics will be thoroughly reviewed and evaluated. Alternative models will be explored that provide a more accurate description of population changes (reduce systematic bias), given available fishery information and biological data. In particular, we will evaluate ways to relax the current assumptions of constant catchability and recruitment. Methods will be explored to combine data from commercial fishing logbooks and research vessel surveys. Methods will be investigated to improve forecasts of lobster abundance based on the model of population dynamics.

Given improved population models and updated estimates of biological parameters, estimates of the overfishing guidelines specified in the FMP for NWHI lobsters will be revised (50 CFR Part 602 Guidelines). These will include estimates of the maximum sustainable yield (MSY) under the current recruitment regime and the optimum spawning potential ratio (SPR). These statistics will be computed by species and bank, where sufficient data permit.

(4) New quota setting procedures

The principal research emphasis will be on devising and evaluating alternative procedures for setting the annual catch quota. As recommended by the review panel, new procedures will be developed that:

Assure greater stability and dependability in the annual catch quota, consistent with goals of the fishing industry;

Establish a catch quota well in advance of the season opening date to ease industry and NMFS planning;

Avoid unnecessary and problematic mid-season quota adjustments; and

Provide adequate protection of the population from recruitment overfishing.

In developing quota procedure options, we will evaluate the performance of alternative methods under a range of assumptions about NWHI lobster population dynamics. The study will employ the best available population model but take into account model misspecification, statistical uncertainty in parameter estimates, and random variation in population processes. Simulation methods, including Monte Carlo and bootstrap resampling, will be used to judge the performance of quota setting options.

We emphasize here that the technical analysis of the Amendment 7 quota formula reported in this document is not part of the study to develop alternative quota procedures, but was undertaken incidentally as part of ongoing work with the lobster population dynamics model. The exact quota formula derived in that analysis will not be among the new alternative quota procedures evaluated.

When a preliminary evaluation of alternative quota methods is completed, NMFS and Council staff will present the options to the Crustaceans Plan Team and the Crustaceans Advisory Panel for consideration and comment. Based on these reviews, the options will be refined and modified to satisfy industry objectives and meet NMFS management requirements. Council and NMFS staff will then draft appropriate documents to amend the Crustaceans FMP and expedite Council adoption and NMFS approval of new quota procedures.

ACKNOWLEDGMENTS

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TABLES

Table 1.--Annual landings of spiny and slipper lobsters (1,000's), trapping effort (1,000 trap-hauls), and the percentage of spiny lobsters in the landings, 1983-94[a].

Year	Spiny lobsters	Slipper lobsters[b]	Total lobsters	Effort	CPUE	Percent spiny lobsters
1983[c]	158	18	176	64	2.75	90
1984	677	207	884	371	2.38	78
1985	1,022	900	1,902	1,041	1.83	57
1986	843	851	1,694	1,293	1.31	54
1987	393	352	745	806	0.92	57
1988	888	174	1,062	840	1.26	84
1989	944	222	1,166	1,069	1.09	81
1990	591	187	777	1,182	0.66	76
1991[d]	131	35	166	296	0.56	79
1992[e]	260	164	424	722	0.59	61
1994[f]	85	46	131	168	0.78	65

[a]Data are provided to the National Marine Fisheries Service as required by the Crustacean Fishery Management Plan of the WPRFMC and compiled by the Fishery Management Research Program, Honolulu Laboratory.

[b]Indicated slipper lobster landings for 1984-87 are 72% of reported landings. The adjustment was made to account for a minimum size change in 1987.

[c]April-December 1983.

[d]January-May and November-December 1991.

[e]January-April and July-December 1992.

[f]July-August 1994.

Table 2.--Synopsis of Northwwestern Hawaiian Islands lobster fishery catch quota management statistics.

Year	Population parameters[1]	N_{opt}	C_{opt}	Preliminary N_{est}	Preliminary quota	Final N_{est}	Final quota	Final catch	Outcome & management action
1992	S = 0.960 R = 1.460 q = 0.914	1,400,000	960,000	1,190,000	750,000	878,000	438,000	424,000	Quota procedure appeared to work well.
1993	S = 0.963 R = 0.838 q = 0.732	1,366,000	220,000	1,065,574	0	no data	0	0	Fishery closed.
1994	S = 0.963 R = 0.838 q = 0.732	1,420,700	200,000	1,420,700	200,000	1,241,600	20,900	131,000	Final quota exceeded; season aborted in August.
1995	S = 0.963 R = 0.756 q = 0.717	1,424,183	134,494	1,328,202	38,513	---	---	---	

[1]S is survival rate in absence of fishing (monthly)

R is recruitment (millions of lobsters per year)

q is catchability (per million trap hauls)

Table 3.--ANOVA statistics for evaluation of bank effect.

Source of variation	Degrees of freedom	Sum of squares	F value (F_{calc})	Prob{$F>F_{calc}$}
Model	115	2018.479	64.88	0.0001 **
Error	6554	1773.110		
Corrected Total	6669	3791.588		
Year	10	1379.963	510.08	0.0001 **
Month	11	188.175	63.23	0.0001 **
Year*Month	91	382.953	15.56	0.0001 **
Bank	3	67.387	83.03	0.0001 **

**Highly significant.

Table 4.--Aggregate annual catch and CPUE (spiny and slipper lobsters combined) for principal lobster fishing banks in the Northwestern Hawaiian Islands, 1983-94. Catch in number of lobsters; CPUE in number of lobsters per trap-haul.

Year	Necker Island		Maro Reef		Gardner Pinnacles		St. Rogatien Bank	
	Catch	CPUE	Catch	CPUE	Catch	CPUE	Catch	CPUE
1983	117,486	2.80	[redacted]	[redacted]	[redacted]	[redacted]	-----	-----
1984	258,907	2.73	309,495	2.22	252,647	2.56	-----	-----
1985	290,781	1.57	721,120	1.88	247,244	1.65	296,438	1.68
1986	225,419	1.07	542,936	1.34	143,073	0.87	178,643	1.30
1987	157,745	0.84	286,808	1.14	64,201	0.58	33,281	0.50
1988	169,648	1.08	531,791	1.39	169,546	1.20	127,906	1.46
1989	349,329	1.11	417,354	1.25	271,497	1.00	84,446	0.95
1990	283,584	0.67	153,104	0.72	296,917	0.60	[redacted]	[redacted]
1991	59,428	0.55	[redacted]	[redacted]	[redacted]	[redacted]	-----	-----
1992	167,197	0.48	139,751	1.01	96,056	0.48	-----	-----
1993	-----	-----	-----	-----	-----	-----	-----	-----
1994	65,581	0.81	[redacted]	[redacted]	42,116	0.61	-----	-----

----- no fishing

[redacted] confidential data

FIGURES

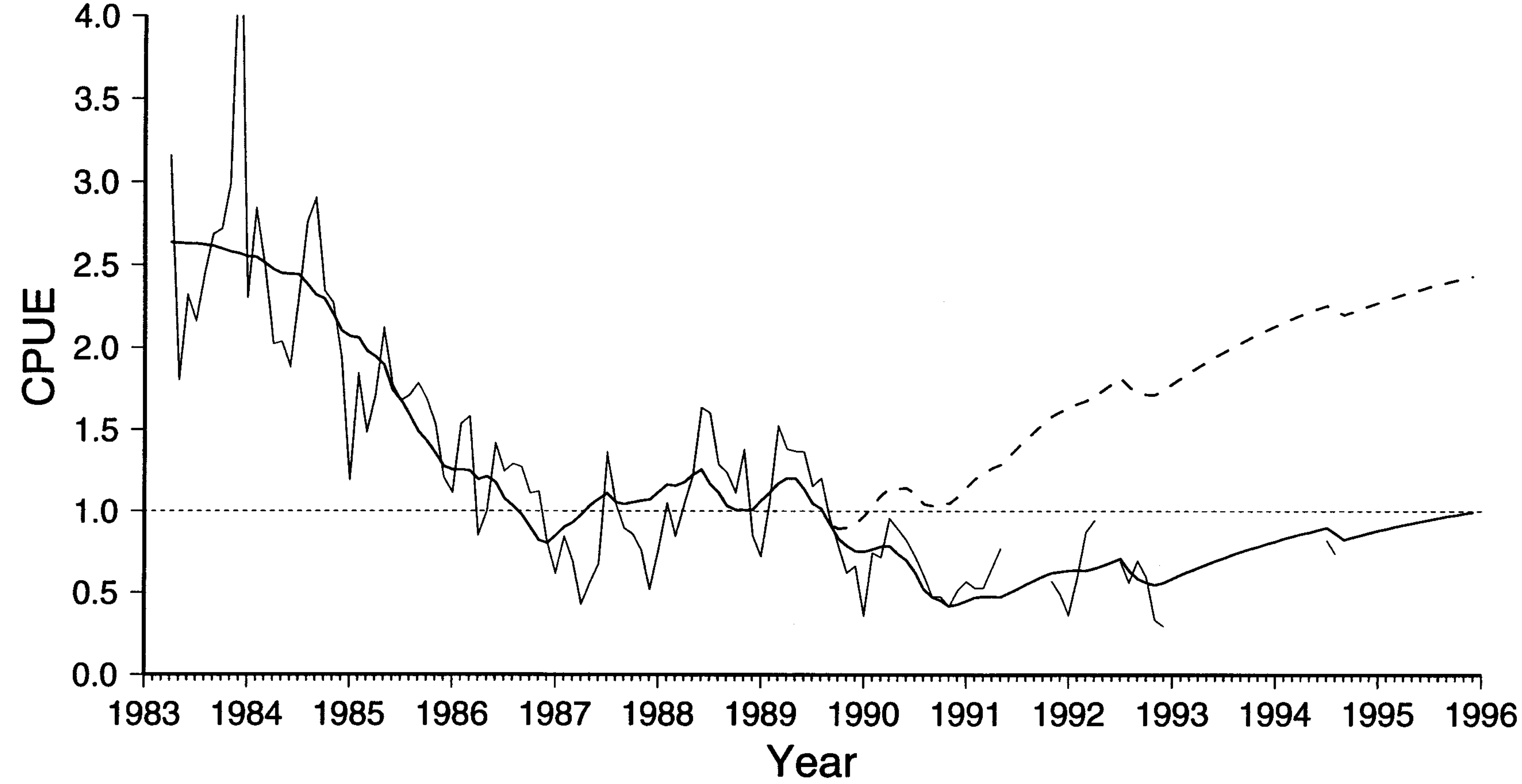

Figure 1.--Observed NWHI lobster CPUE (species combined, all banks) and fitted population models assuming a constant level of recruitment (dashed line), and assuming a decrease in annual recruitment level after October 1989 (solid line).

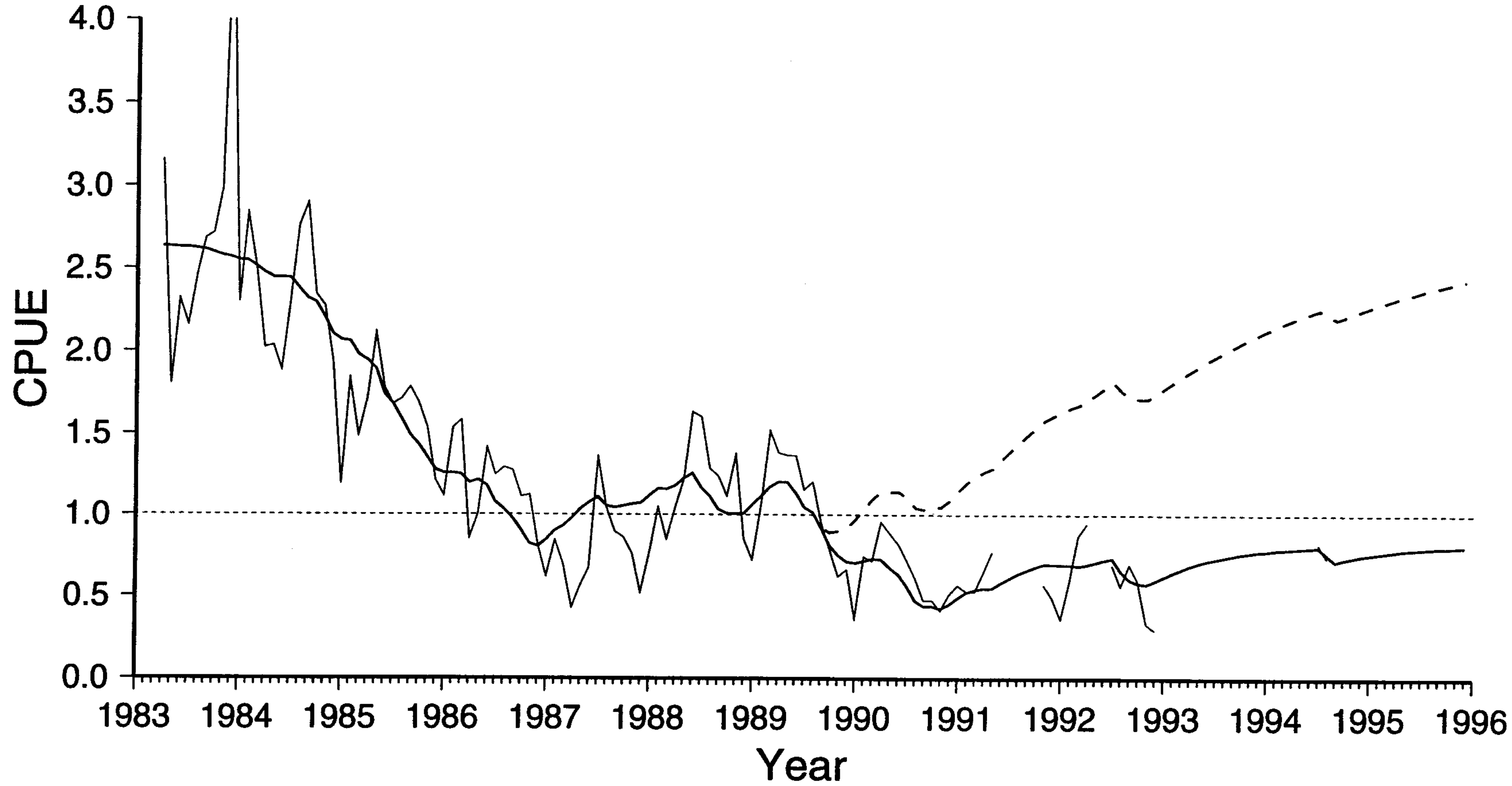

Figure 2.--Observed NWHI lobster CPUE (species combined, all banks) and fitted population models assuming a constant natural mortality rate (dashed line), and assuming an increase in natural mortality after October 1989 (solid line).

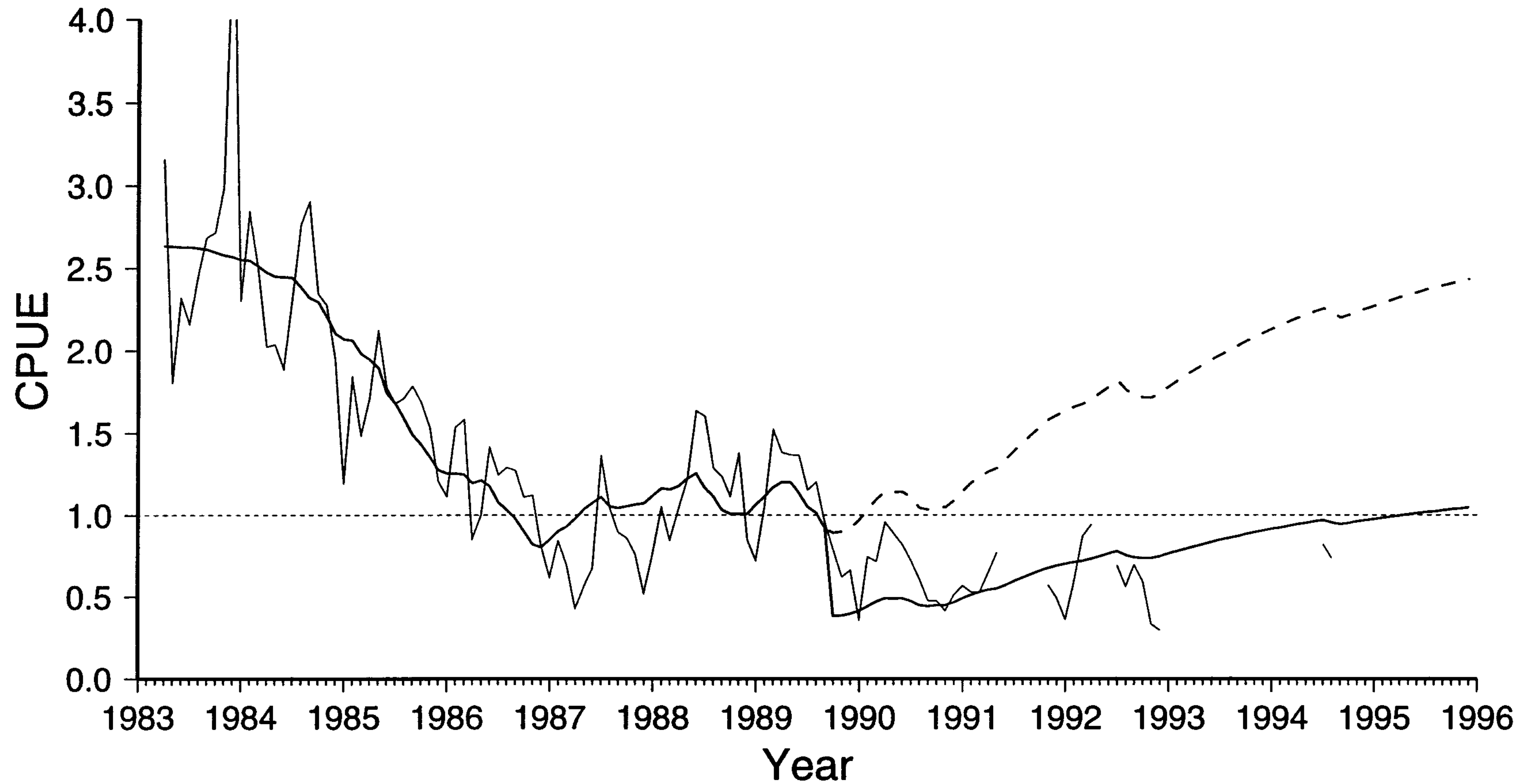

Figure 3.--Observed NWHI lobster CPUE (species combined, all banks) and fitted population models assuming a constant catchability (dashed line), and assuming an decrease in catchability after October 1989 (solid line).

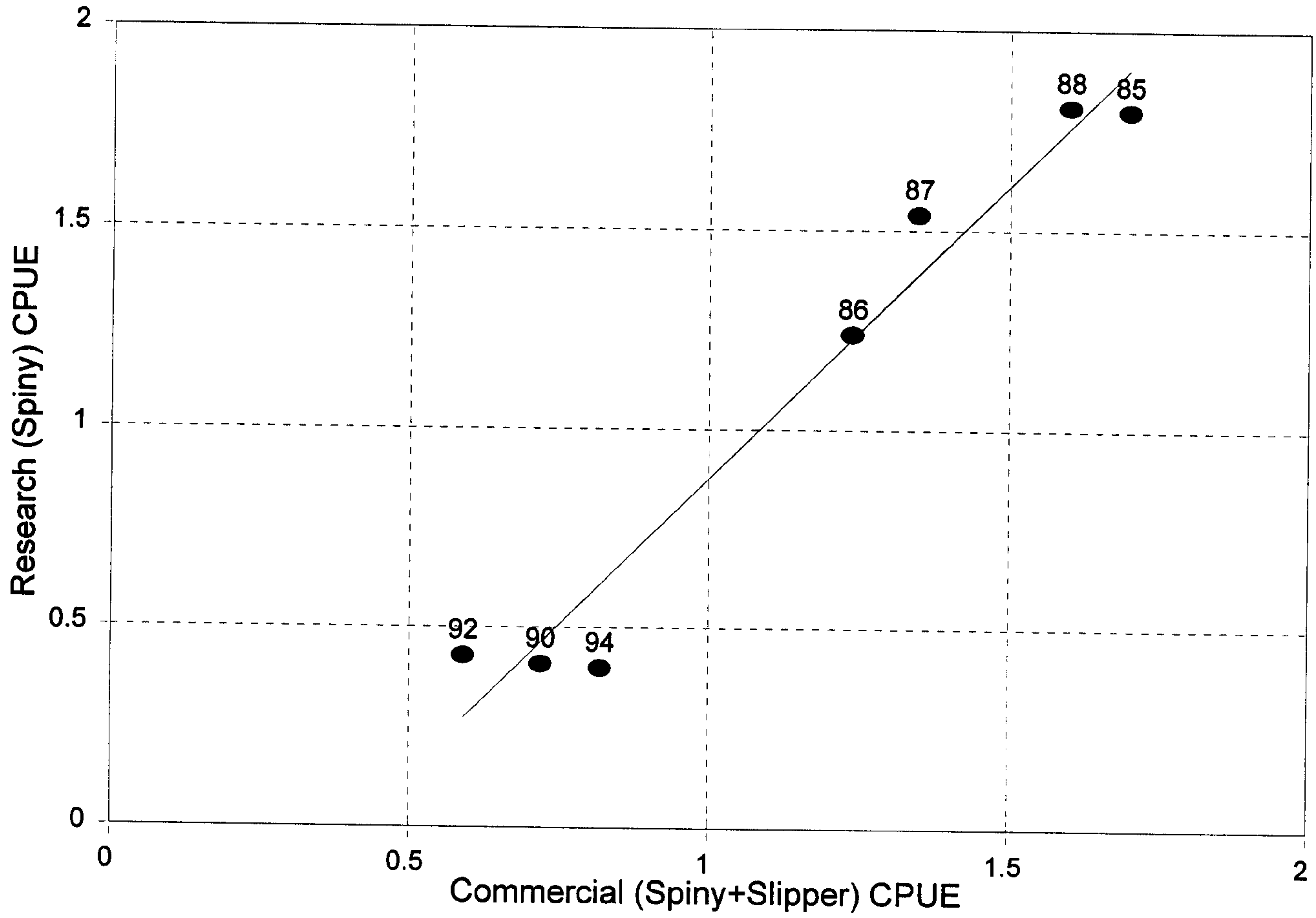

Figure 4.--Relationship between *Townsend Cromwell* (research) CPUE of spiny lobsters and commercial vessel CPUE of spiny and slipper lobsters in the same month, with year of fishing indicated.

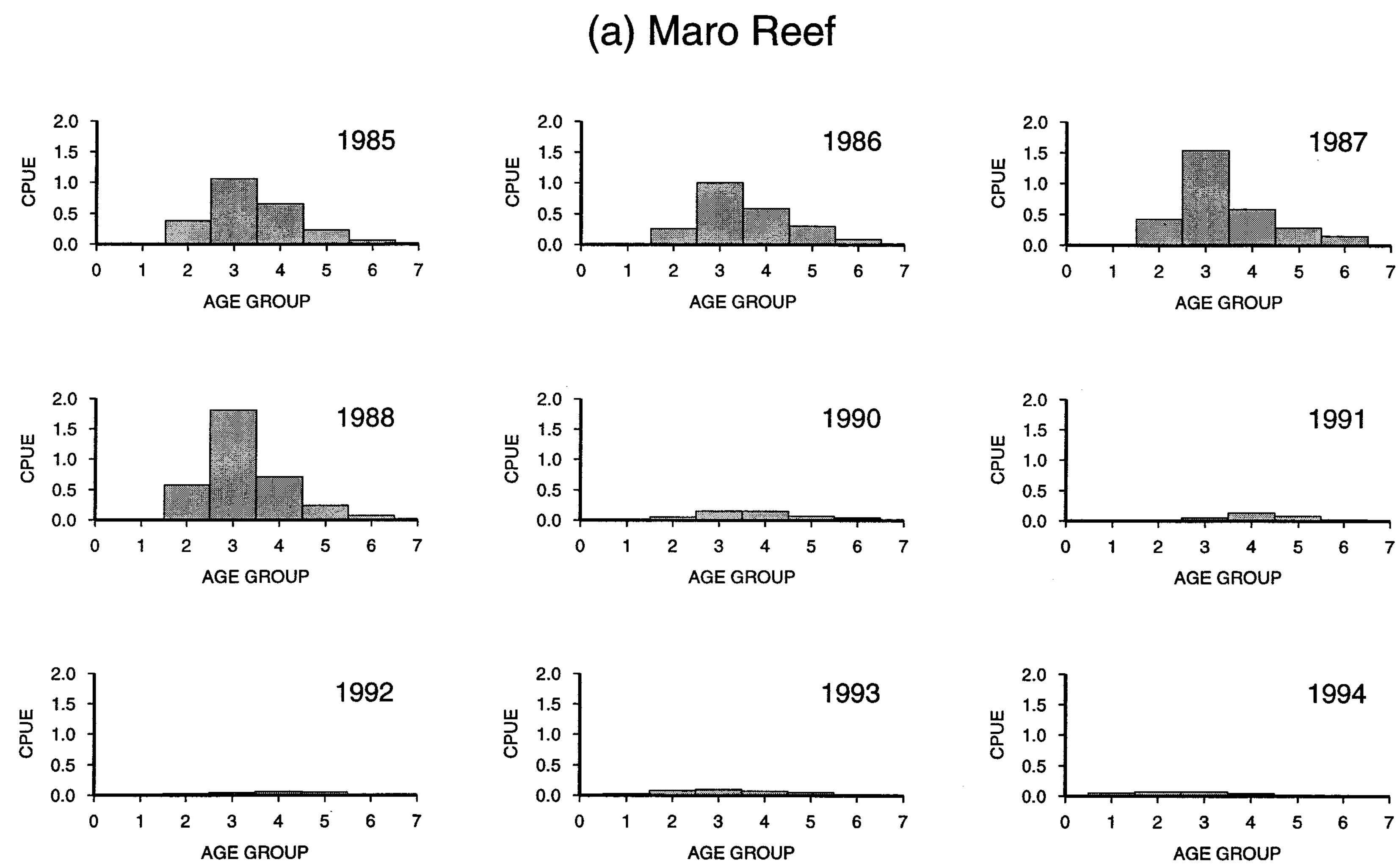

Figure 5.--Age-composition of spiny lobsters caught in the *Townsend Cromwell* research surveys. (a) Maro Reef.

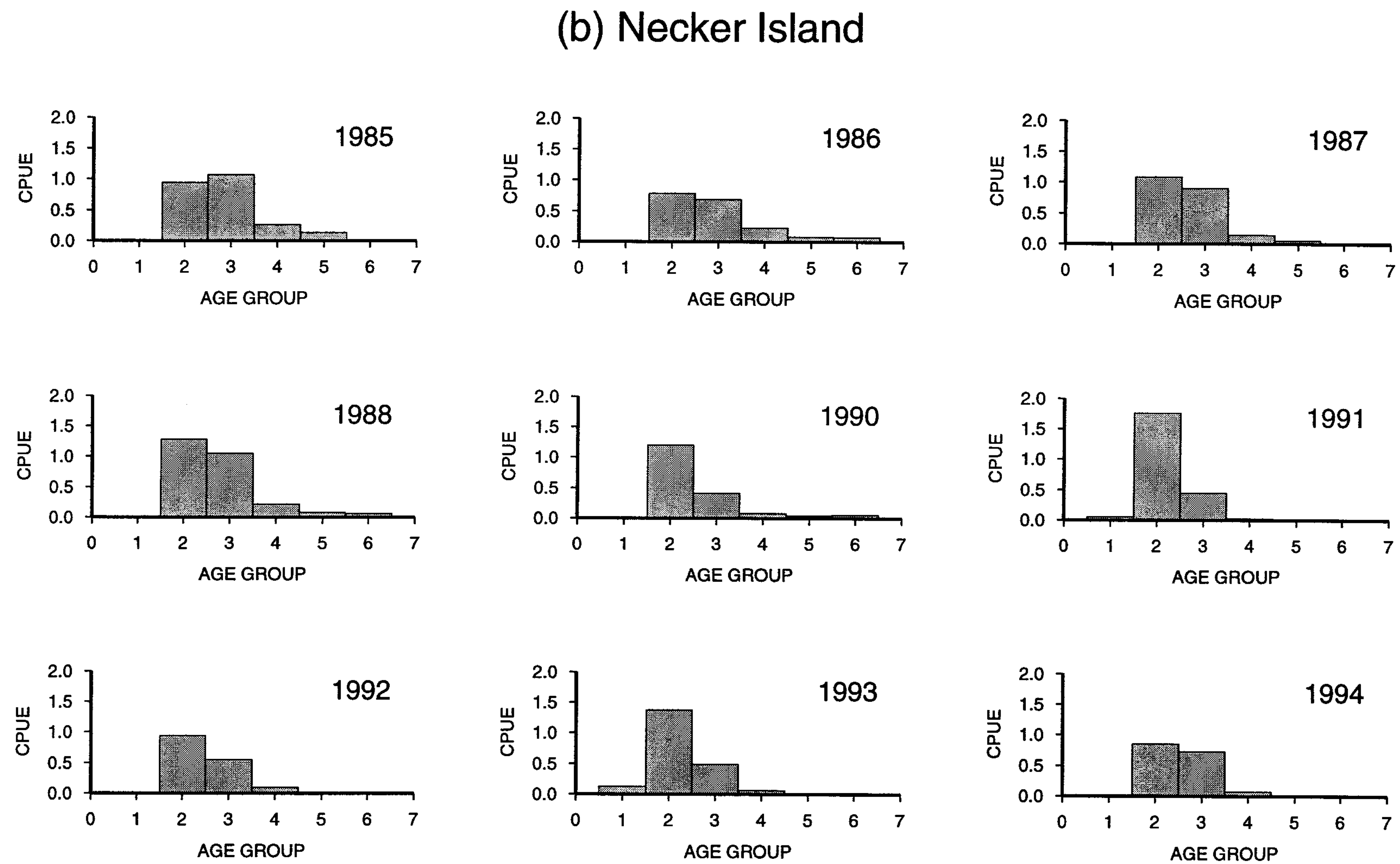

Figure 5.--Age-composition of spiny lobsters caught in the *Townsend Cromwell* research surveys. (b) Necker Island.

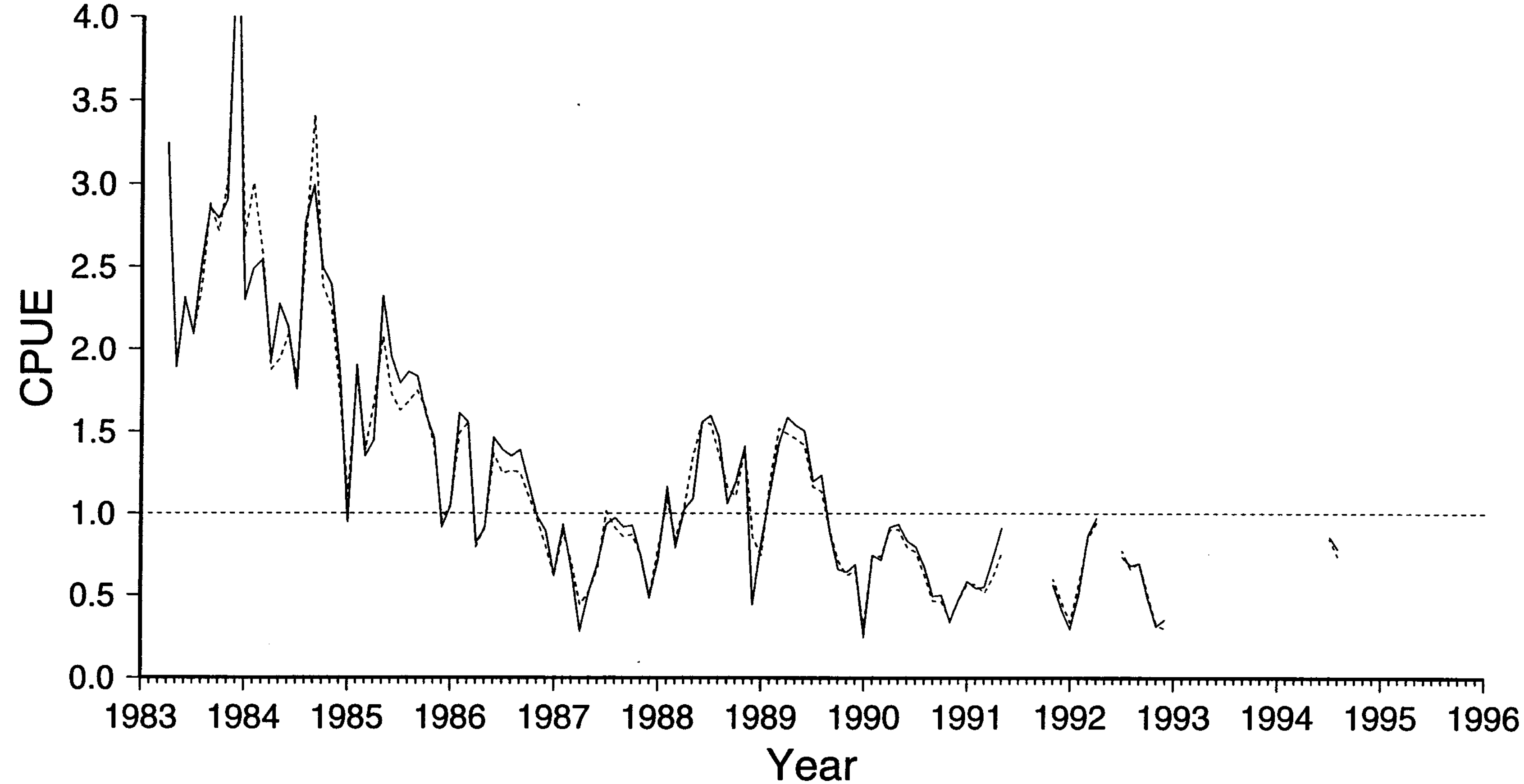

Figure 6.--Observed NWHI lobster CPUE (species combined, all banks) computed from vessel-day catch and effort statistics (dashed line) and corresponding "least squares means" average CPUEs adjusted for bank effects (solid line).

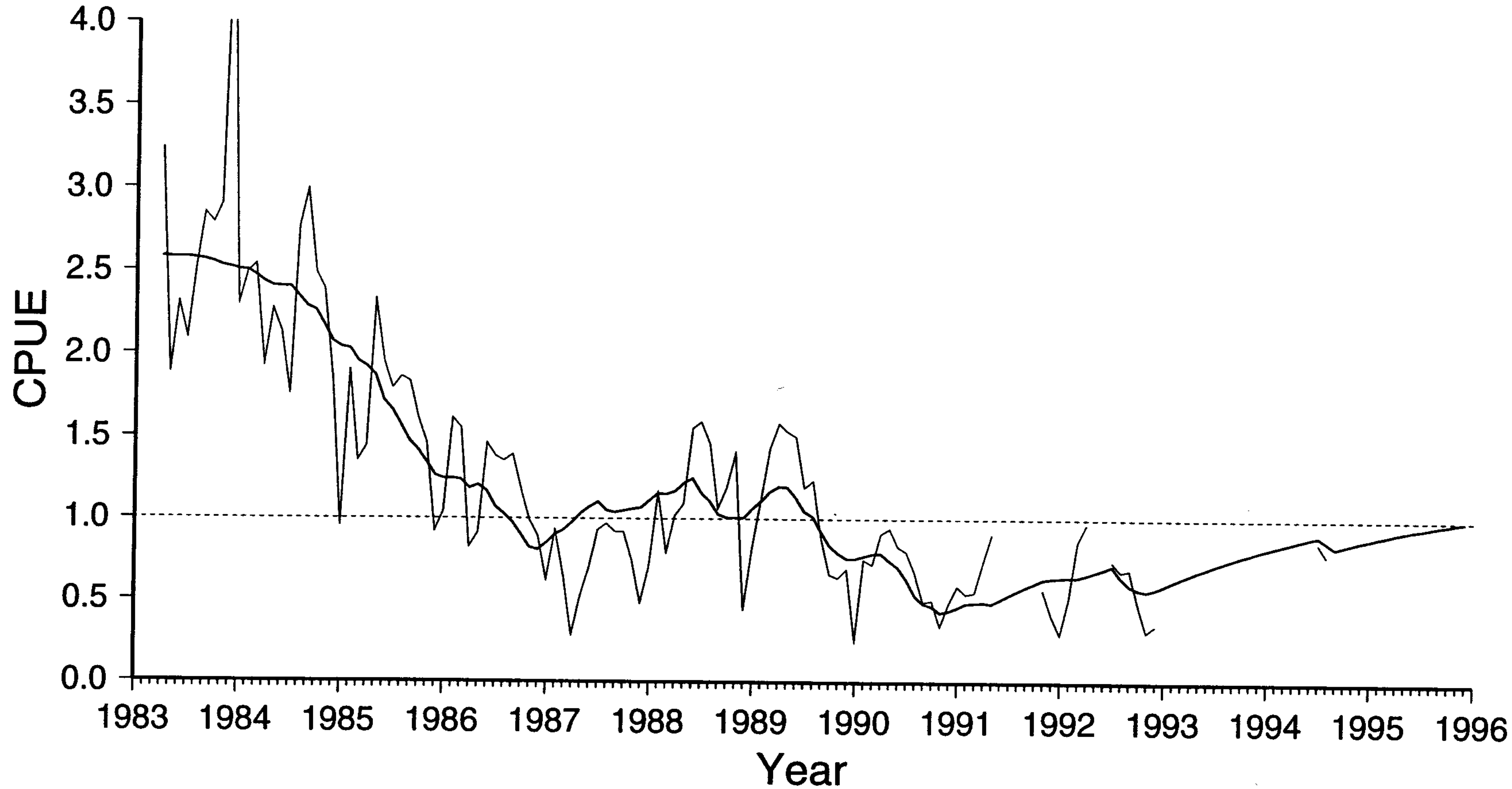

Figure 7.--Bank-adjusted average NWHI lobster CPUE (species combined, all banks) and fitted population model used to project July 1995 lobster population.

APPENDIX

APPENDIX

Discrete Model of Lobster Population and Harvest

This appendix describes the mathematical model of lobster population dynamics and harvest, and derivation of the optimum catch, optimum population size, and annual catch quota.

Definitions and Notation

N_i = Population size at the beginning of the i-th month (i = 1, 2, ... , 13).

C_i = Number of lobsters caught in the i-th month of an n-month fishing season (i = 1, 2, ... , n). We assume that all lobsters caught are killed, whether retained or returned to the sea.

C_{tot} = Total catch during the fishing season.

N_{opt} = Optimum population size at beginning of the fishing season. This is the initial population size large enough to allow the fleet to achieve a target average catch rate, Θ_{opt}, during the fishing season and to enable the stock to rebuild during the closed period to the same population size at the start of the following fishing season (a management goal).

N_{est} = Estimated population size at the beginning of the fishing season.

C_{opt} = Optimum catch. This is the catch that if taken from a population starting at N_{opt} will achieve the target Θ_{opt} and allow the population to rebuild to N_{opt} by the beginning of the following fishing season.

R_i = Number of lobsters recruiting to the harvestable stock during the i-th month (i = 1, 2, ... , 12).

R_{tot} = Total recruitment during the year.

M = Natural mortality coefficient (per month).

S = Natural monthly survival rate, defined as e^{-M}.

q = Catchability coefficient (per trap-haul).

n = Number of months in the fishing season.

$CPUE_i$ = Average number of lobsters caught per trap-haul during the i-th month of the fishing season,

$= q\, N_i$

Θ = Average number of lobsters caught per trap-haul during the entire fishing season,

$= (q/n)\ \{N_1 + N_2 + ... + N_n\}$

Θ_{opt} = Optimum value of Θ (a management goal).

Q^* = Annual catch quota derived from the population model (exact).

Q = Annual catch quota specified in Amendment 7 to the Crustaceans FMP (an approximation to Q^*).

β = A coefficient in the exact catch quota formula.

μ = Optimum harvest ratio.

δ = Relative discrepancy between the approximate and exact catch quotas.

Δ = Relative difference between the estimated July population size, N_{est}, and the optimum population size, N_{opt}.

Population Dynamics

The model of population dynamics assumes that natural mortality is proportional to the population size at the beginning of a month, whereas monthly recruitment occurs at a constant rate equal to $R_{tot}/12$. The population dynamics are described by the difference equation:

$$\begin{aligned} N_{i+1} &= N_i - N_i(1-S) - C_i + R_{tot}/12 \\ &= N_i S - C_i + R_{tot}/12\ . \end{aligned} \tag{1}$$

In the absence of a fishery the population size at the start of each month will tend toward a constant, maximum size determined by the monthly recruitment and natural mortality rate:

$$N_{max} = \frac{R_{tot}/12}{(1-S)}\ . \tag{2}$$

Assume that fishing is allowed during the first n months of the year (in our context, the year begins on July 1), followed by a closed period of (12-n) months. Algebraic manipulation of Equation (1) yields a general expression for the population size at the beginning of the i-th month of the fishing season in terms of the population at the beginning of the year:

$$N_i = N_1 S^{i-1} + \frac{(1-S^{i-1})}{(1-S)} [R_{tot}/12 - C_{tot}/n] , \tag{3}$$

for i = 1, 2, ... , n

Similarly, the population size at the beginning of the j-th month after the fishery closes is:

$$N_{n+j} = N_1 S^{n+j-1} - \frac{S^{j-1}(1-S^n)}{(1-S)} C_{tot}/n + \frac{(1-S^{n+j-1})}{(1-S)} R_{tot}/12 , \tag{4}$$

for j = 1, 2, ... , (13-n)

In particular, Equation (4) can project the population size at the beginning of "month 13"; i.e., at the beginning of the next fishing season:

$$N_{13} = N_1 S^{12} - \frac{S^{12-n}(1-S^n)}{(1-S)} C_{tot}/n + \frac{(1-S^{12})}{(1-S)} R_{tot}/12 . \tag{5}$$

Optimum Population and Catch Levels

A key objective of the Council has been to maintain a constant population size at the beginning of each year, N_{con}. To find this equilibrium population size, set $N_{13} = N_1 = N_{con}$ in Equation (5) and solve for N_{con}:

$$N_{con} = N_{max} - \frac{S^{12-n} - S^{12})}{(1-S)(1-S^{12})} C_{tot}/n . \tag{6}$$

Clearly, N_{con} depends on C_{tot} and n, as well as S and R. Note that in the absence of a fishery, the population size at the beginning of every month is constant at a level of N_{max}. If a fishery is operating the population begins each fishing season at N_{con}, but otherwise is less than N_{con}, declining during the fishing season and rebuilding during the closed period.

In addition to stabilizing the population size, the Council has chosen to achieve a particular average CPUE during the fishing season, Θ. We can derive Θ using Equation (3) as:

$$\begin{aligned} \Theta &= \frac{q}{n} [N_1 + N_2 + ... + N_n] \\ &= \frac{q}{n(1-S)} [N_1(1-S^n) + (n - 1 - \frac{S(1-S^{n-1})}{(1-S)}) (R_{tot}/12 - C_{tot}/n)] . \end{aligned} \tag{7}$$

Combining the last two results, we can find the total annual catch, $C_{tot} = C_{opt}$, that will stabilize the population size at the beginning of each fishing season while also achieving an optimum (target) average CPUE, $\Theta = \Theta_{opt}$. Substituting N_{con} for N_1 in Equation (7) and solving for C_{opt} gives:

$$C_{opt} = n\left[\frac{(n - 1 - S(1-S^{n-1}))}{(1-S)(1-S^n)} + \frac{(S^{12-n} - S^{12})}{(1-S)(1-S^{12})}\right]^{-1} \times \left[N_{\max} + \frac{(n - 1 - S(1-S^{n-1}))}{(1-S)(1-S^n)} R_{tot}/12 - \frac{n(1-S)\Theta_{opt}}{q(1-S^n)}\right] . \quad (8)$$

With appropriate substitutions we can also derive the corresponding optimum stable population size, N_{opt}, in terms of C_{opt} and Θ_{opt}:

$$N_{opt} = \frac{n(1-S)\Theta_{opt}}{q(1-S^n)} - \left[\frac{(n-1)}{(1-S^n)} - \frac{S(1-S^{n-1})}{(1-S)(1-S^n)}\right] (R_{tot}/12 - C_{opt}/n) . \quad (9)$$

Setting the Catch Quota

Equation (5) may be used to determine the annual catch quota, Q^*, defined as the maximum catch that can be taken, given knowledge of the July lobster abundance, while allowing the population to recover to the desired level of N_{opt} at the beginning of the following fishing season. Let N_{est} denote an estimate (e.g., a pre-season model forecast or within-season survey estimate) of the July population size. Then Equation (5) may be reformulated as:

$$N_{opt} = N_{est}S^{12} - \frac{S^{12-n}(1-S^n)}{(1-S)} Q^*/n + \frac{(1-S^{12})}{(1-S)} R_{tot}/12 . \quad (10)$$

Solving Equation (10) for Q^*, we have:

$$Q^* = C_{opt} + \beta\ [N_{est} - N_{opt}] , \quad (11)$$

where

$$\beta = \frac{nS^n(1-S)}{(1-S^n)} .$$

Thus the optimum quota depends not only on C_{opt}, N_{opt}, and N_{est}, but on the duration of the fishing season and the natural mortality rate through the coefficient ß. The quota formula specified in Amendment 7 neglects the effects of natural mortality and therefore is an approximation to Q^*:

$$Q = C_{opt} + [N_{est} - N_{opt}] . \quad (12)$$

The discrepancy introduced by the Amendment 7 quota formula, relative to the exact optimum quota is:

$$\delta = \frac{Q - Q^*}{Q^*} = \frac{(1 - \beta)\Delta}{\mu + \beta\Delta} , \tag{13}$$

where

$$\Delta = \frac{N_{est} - N_{opt}}{N_{opt}} ,$$

and

$$\mu = \frac{C_{opt}}{N_{opt}}$$

is the optimum harvest ratio.